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Mixed-Layer Hindcasts Conducted at OWS Victor with Initialization from Synthetic Profiles/Mixed-Layer Hindcasts Conducted with BTs Taken During 1990 with Atmospheric Forcing from NOGAPS

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13. ABSTRACT (Maximum 200 words)

Mixed-layer hindcasts were conducted with data from Ocean Weathership Station Victor (164° E, 34° N) to investigate the question of whether the near-surface thermal structure of synthetic temperature profiles that are determined from observations of sea-surface height (SSH) and sea-surface temperature (SST) can be improved by mixed-layer hindcasting. Synthetic profiles were calculated at Victor based on the SSH and SST of observed deep temperature profiles. Mixed-layer hindcasts were initialized from the synthetic profiles, forced with wind stresses and heat fluxes calculated from 3-h meteorological observations at Victor, and integrated up to the time the observed profiles were taken. Hindcast durations ranged from 12 to 120 h. The mixed-layer depths (MLDs) of the synthetic and hindcast profiles were compared with the MLDs of the observed profiles, and mean and root-mean-square (rms) MLD errors were calculated on a monthly and annual basis.

Overall, the rms MLD error of the hindcast profiles was lower than that of the synthetic profiles. However, the improvement was due mainly to the shallow MLD bias of the synthetic profiles relative to the observed MLDs in the fall and winter. For May through August, when we expected the hindcasts to show the most skill, the rms MLD error of the hindcasts was generally worse than that of the synthetic profiles. An inspection of the individual hindcasts in June and July showed a number of instances where the observed MLD was deeper than would be expected during light winds and strong heating, and shallower than would be expected when the winds were stronger. Such discrepancies might be due to errors in the observed temperature profiles or might be caused by advection, since Victor is located in the Kuroshio Extension, a region of strong mesoscale activity.

A separate mixed-layer hindcast experiment was conducted with standard bathythermograph (BT) observations and atmospheric forcing from the Navy Operational Global Atmospheric Prediction System (NOGAPS) to investigate the question of whether the near-surface thermal structure of climatological temperature profiles can be improved by mixed-layer hindcasting with atmospheric forcing from NOGAPS. For each of the observed BTs, a mixed-layer hindcast was initialized from the Generalized Digital Environmental Model (GDEM), forced with NOGAPS wind stresses and heat fluxes up to the time the observed BT was taken, and verified against the observed BT. Sets of hindcasts were conducted with durations that ranged from 12 to 120 h. The data were for April through September of 1990.

Hindcast skill (the improvement of the rms hindcast error over the rms climatological error) for MLD was positive but fairly low overall, about 4%. The overall hindcast skill was highest in the midlatitude North Atlantic (3% to 15%) and the northeast Pacific (6% to 18%), and was lowest in the northwest Pacific (-10% to 4%) and at low and high latitudes.

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CONTENTS

MIXED-LAYER HINDCASTS CONDUCTED AT OWS VICTOR WITH INITIALIZATION FROM SYNTHETIC PROFILES/MIXED-LAYER HINDCASTS CONDUCTED WITH BTS TAKEN DURING 1990 WITH ATMOSPHERIC FORCING FROM NOGAPS

I. INTRODUCTION

Martin (1994b) demonstrated that mixed-layer hindcasting can improve the mixed-layer depth (MLD) and the near-surface stratification of climatological temperature profiles. Figure 1 (Martin 1994b) shows the root-mean-square (rms) MLD error for mixed-layer hindcasts conducted with data from the Mixed-Layer Experiment (MILE). Hindcasts were initialized both from observed temperature profiles, and from climatological profiles. Figure 1 illustrates that the rms MLD error for hindcasts initialized from climatological temperature profiles decreases as the duration of the hindcasts is increased, and after about 2 d is similar to the rms error for hindcasts initialized from observed temperature profiles. (The rise in the hindcast error after 3 d in Fig. 1 is likely due to the short period of the MILE data [20 d] relative to the length of the longer hindcasts, i.e., fewer cases were run at the longer hindcast durations.) Figure 2 shows results for August from a similar experiment
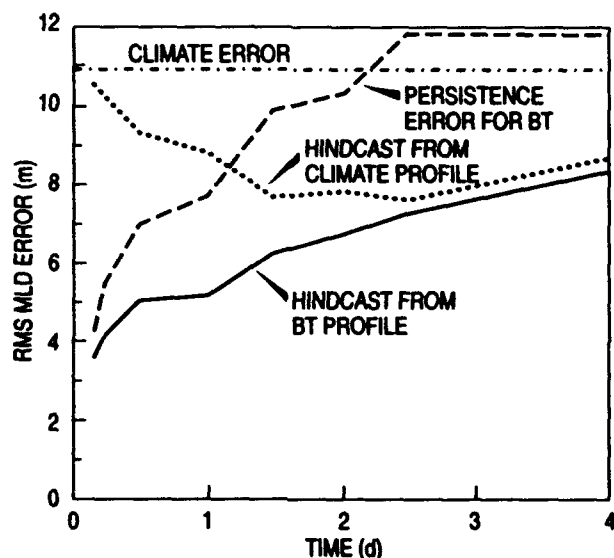
Figure 1. The rms MLD error for mixed-layer hindcasts conducted with data taken during MILE, plotted as a function of the duration of the hindcasts. The rms MLD error is shown for hindcasts initialized from observed temperature profiles and for hindcasts initialized from climatological temperature profiles. The hindcast errors are compared with the errors for persistence and climatology.

Figure 2. The rms MLD error for mixed-layer hindcasts conducted with data taken at OWS Papa between 1960 and 1968 during August. MLD error is shown for hindcasts initialized from observed temperature profiles and for hindcasts initialized from climatological temperature profiles. Error is plotted as a function of the duration of the hindcasts. The hindcast errors are compared with the errors for persistence and climatology.

1

conducted with data taken at Ocean Weathership Station (OWS) Papa over a period of several years (Martin 1994b). The Papa data are not as accurate as the data taken during MILE; hence, the estimates of hindcast skill for MLD tend to be lower with the Papa data than with the MILE data, especially for the shorter hindcasts. However, the results with the several years of Papa data are qualitatively similar to the MILE results: notably, the rms MLD error for hindcasts initialized from climatological profiles is about the same as the error for hindcasts initialized from observed profiles after 2 to 3 d.
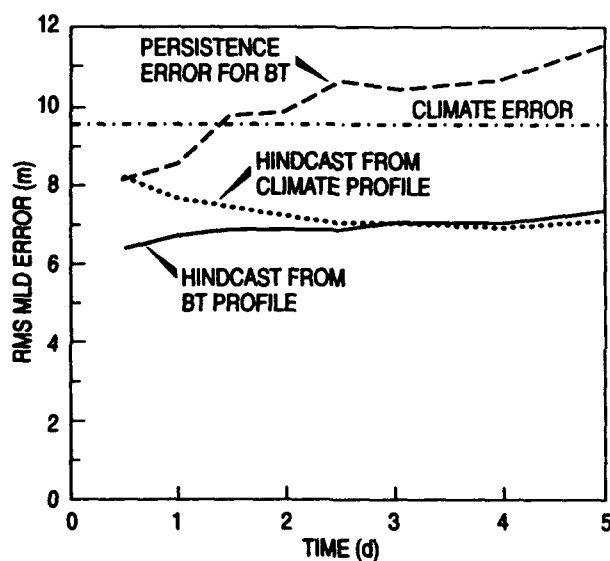
The rms MLD error of mixed-layer hindcasts initialized from climatological temperature profiles is reduced because the MLD and near-surface stratification adjust to the atmospheric forcing during the hindcasts. The adjustment occurs primarily between the surface and (approximately) the maximum depth of the surface mixing. Below the maximum depth reached by the surface mixing, the stratification of the hindcast temperature profiles tends to reflect its initial value.

As the duration of the hindcasts is increased, there is more likelihood that the surface mixing will penetrate deeper into the water column and bring the deeper stratification into adjustment with the surface forcing. However, at the same time, error will tend to increase due to biases in the model and in the atmospheric forcing, and to the neglect of advective processes. Thus, there is a limit to the optimum duration of hindcasts conducted to improve climatological profiles. The limit is probably somewhat dependent upon the region, the season, and upon what aspect of the temperature profiles is to be improved (e.g., the MLD or the near-surface sound-channel depth).

It might be expected that the improvement to climatological temperature profiles from mixed-layer hindcasting at middle and high latitudes would be mainly restricted to the heating season in spring and summer when net heating of the ocean through the surface occurs. When net surface heating occurs, the mixed layer may either deepen or shallow in response to the atmospheric forcing. When there is net cooling of the ocean by the atmosphere, however, a local mixed-layer hindcast can only increase the MLD; it cannot shallow a mixed layer that is initially too deep.

Because direct subsurface ocean observations are scarce, operational ocean analyses, such as those performed at the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC) and the Naval Oceanographic Office (NAVOCEANO), make extensive use of climatological and "synthetic" profiles. Synthetic profiles are generated from observations of sea surface height (SSH) and/or sea surface temperature (SST), based on relations between these quantities and subsurface thermal structure determined from historical data (Carnes et al. 1994). Mixed-layer hindcasting may be able to improve the operational ocean analyses by improving the near-surface stratification of both climatological and synthetic profiles.

The experiments discussed in this report were undertaken by the Naval Research Laboratory (NRL) to address two questions:

• Can mixed-layer hindcasting improve synthetic temperature profiles?

• Does mixed-layer hindcasting with operational atmospheric forcing show skill over climatology?

Since synthetic profiles are derived from SSH and SST, they provide a means of estimating subsurface structure from surface parameters that can be obtained from satellite observations. In regions of strong fronts, synthetic profiles can capture a large fraction of the variability in the lowest vertical modes because of the signature of this variability in SSH and SST. However, it might be expected that synthetic profiles would not be much better than regular climatological

profiles in terms of their near-surface thermal structure. If this were the case, the near-surface thermal structure of synthetic profiles should generally be improved by mixed-layer hindcasting.

Hence, it appeared to be worthwhile to investigate the improvement to synthetic profiles that could be gained from mixed-layer hindcasting. Data from OWS Victor, located in the Kuroshio Extension (164° E, 34° N), were selected to be used for this study. The Naval Research Laboratory's Data Assimilation, Research, and Transition (DART) Project, which has been working on a forecast system for the western North Pacific, has developed software to derive synthetic profiles from SSH and SST for this region, and the data from Victor contain the oceanic and meteorological observations needed to derive synthetic profiles and to conduct mixed-layer hindcasts. Mixed-layer hindcasts were initialized from synthetic profiles derived from the deep observed temperature and salinity profiles available at Victor, forced with atmospheric forcing calculated from the Victor 3-h meteorological observations, and verified against the observed temperature profiles. The MLD error of the profiles resulting from the mixed-layer hindcasts was compared with the error of the synthetic profiles.

Most of the mixed-layer hindcast studies that have been performed to date have used local meteorological observations to calculate atmospheric forcing. However, the Navy operational ocean analysis and prediction models generally use atmospheric forcing from the Navy atmospheric models—either the Navy Operational Global Atmospheric Prediction System (NOGAPS) or the Navy Operational Regional Atmospheric Prediction System (NORAPS). It might be expected that the surface wind stresses and heat fluxes from these models would not be as accurate as those determined from local meteorological observations, especially in areas of the open ocean where few data are being assimilated into the atmospheric models. Since errors in the atmospheric forcing will cause errors in the mixed-layer hindcasts, there is a question as to how much skill (with respect to climatology) the operational mixed-layer hindcasts have in predicting the near-surface thermal stratification and the MLD.

To investigate this question, the following experiment was conducted. Bathythermograph (BT) observations and NOGAPS surface wind stress and heat flux fields were obtained for 1990. Mixed-layer hindcasts were initialized from the Generalized Digital Environmental Model (GDEM) climatology at the location of each of the observed BTs, but prior to the time the BTs were taken. Then the GDEM profiles were hindcast up to the time the observed BTs were taken (using the NOGAPS wind stresses and heat fluxes for atmospheric forcing) and validated against the observed BTs. The MLD error of the hindcast profiles, relative to the observed profiles, was compared to the error of the original GDEM climatological profiles.

A potential source of trouble for both of these studies is that small errors in the observed temperature profiles can lead to significant errors in determining the actual MLD. The MLD is typically defined as the depth at which the temperature is about 0.2°C less than the SST. This change in temperature is relatively small and is thus somewhat susceptible to both measurement and recording errors.

II. IMPROVEMENT TO SYNTHETIC PROFILES FROM MIXED-LAYER HINDCASTING WITH DATA FROM VICTOR

Synthetic temperature profiles are generated from surface observations of SSH and/or SST by means of relations (determined from historical data) between these quantities and subsurface thermal structure. Within the present operational analyses, synthetic profiles are generated using empirical orthogonal functions (EOFs), although in analyses currently under development at NRL they are obtained from averages of historical profiles binned according to SSH and SST (Mike Carnes, NRL,

personal communication). Synthetic profiles primarily account for the variability in the largest vertical scales. This is because when considering data taken over a period of many years, SSH and SST do not generally correlate well with the thermal or salinity structure on small vertical scales. Therefore, we expect that the near-surface structure of synthetic profiles would not be much better than climatology and, like climatological profiles, could be improved by mixed-layer hindcasting.

Data from Victor were used to investigate the improvement to synthetic profiles from mixed-layer hindcasting for several reasons: (1) meteorological data with good temporal resolution (3 h) are available at Victor to calculate atmospheric forcing; (2) deep temperature anc salinity profiles, which can be used to calculate synthetic profiles and validate hindcasts, are available over a period of several years; and (3) software was available from the DART Project to calculate synthetic profiles at this location. Since Victor is located in the Kuroshio Extension, where the subsurface thermal structure is highly variable due to the meandering of the Kuroshio current, the experiment would provide a good test of the ability of mixed-layer hindcasts to improve the near-surface thermal structure of synthetic profiles in a region of strong dynamics. At the same time, of course, advective effects tend to increase the error of MLDs calculated with single-station models.

A previous mixed-layer hindcast study that used data from Victor (Martin 1994a), in which the hindcasts were initialized with and validated against observed profiles, showed skill* in hindcasting MLD of 11% for 48-h hindcasts, calculated on an annual basis. The hindcast skill for MLD was higher in spring and summer than in fall and winter (17%, 12%, 10%, and 4%, respectively, for 48-h hindcasts), and increased as the duration of the hindcasts was increased from 12 to 48 h. Hindcast skill at Victor was lower than that calculated at November and Papa. It was presumed that this was due to the much stronger advective effects at Victor (November and Papa are located in the relatively quiescent northeast Pacific at 140° W, 30° N and 145° W, 50° N, respectively).

A. Hindcast Experiments at Victor Using Deep Profiles

Deep (>1000 m) temperature and salinity profiles at the location of Victor for the years 1960 through 1972 were extracted from the Master Oceanographic Observation Data Set (MOODS) at NAVOCEANO (Victor was terminated in 1972). These were processed to eliminate erroneous or unsuitable profiles (about 3% of the profiles were eliminated by this processing). The resulting data set contained 1343 pairs of temperature and salinity profiles taken between 1964 and 1972.

A pair of synthetic temperature and salinity profiles was generated for each pair of observed temperature and salinity profiles using the Modular Ocean Data Assimilation (MODAS) software developed within the DART Program (Carnes et al. 1993). The calculation of synthetic temperature and salinity profiles with MODAS depends on the location, time of year, SST, and SSH, which can be calculated from the observed temperature profile. (Only the observed temperature profile was used by MODAS to calculate the SSH and the synthetic temperature and salinity profiles.) To calculate SSH, the deep temperature profiles were extended to 2000-m depth with the climatology of Beatty (1977).

Atmospheric forcing was calculated from the 3-h meteorological observations at Victor using standard bulk formulas (Martin 1994a). The Garratt (1977) drag coefficient was used to calculate the wind stress, and a coefficient of 0.0014 was used to calculate the latent and sensible heat fluxes. The coefficients were corrected for atmospheric stability (Kondo 1975). The solar radiation was

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*defined as the .mprovement of the hindcast rms error over the persistence rms error

calculated with the formula of Fritz (List 1958) and the cloud correction of Reed (1977). The surface albedo was taken to be 6% and the Jerlov (1968) Type IA extinction profile was used to describe the attenuation of solar radiation with depth.

The Price mixed-layer model (Price et al. 1986; Martin 1986) was used for the hindcasts. The model integrations were conducted on a stretched vertical grid with a resolution of 1 m at the surface, a 6% increase in the thickness of each successive layer with depth, and a maximum depth of 1000 m. The model timestep was 600 s.

Mixed-layer hindcasts were initialized from the synthetic temperature and salinity profiles and integrated up to the time the corresponding observed profiles were taken. Several sets of hindcasts were conducted with durations ranging from 12 to 120 h, i.e., the hindcasts were initialized 12 to 120 h before the observed profiles were taken and then integrated up to the time of the observed profiles. The MLDs for the synthetic and hindcast profiles were compared with the MLDs of the observed profiles. Mean and rms errors for the synthetic and hindcast MLDs were calculated on a monthly and annual basis for hindcasts of different duration and for different definitions of MLD. The MLD was defined as the depth at which the temperature became 0.1°C to 0.5°C less than the SST (the most commonly used definition of MLD is the depth at which the temperature becomes 0.2°C less than the SST).

Table 1 summarizes the mean and rms MLD errors calculated on an annual basis. MLD errors are also shown for three different climatologies. The climatologies include the GDEM; a "BT climatology," calculated by averaging observed temperature profiles from Victor at 5-m intervals of depth; and an "MLD climatology," obtained by averaging the MLDs from the observed temperature profiles at Victor. The BT and MLD climatologies employed over 12,000 mechanical bathythermograph (MBT) profiles taken at Victor between 1960 and 1972.

Table 1 indicates that, relative to the observed profiles, the synthetic profiles have a shallow MLD bias of about 10 m and an rms MLD error of 30–32 m (calculated on an annual basis). The

Table 1 — Comparison of the Mean and rms MLD Error at Victor for 12- to 120-h Mixed-Layer Hindcasts with the MLD Error of the Synthetic Profiles Used to Initialize the Mixed-Layer Hindcasts

	Mean MLD Error (m)				rms MLD Error (m)			
	MLD Criteria (°C)							
Hindcast Duration (h)	0.1	0.2	0.3	0.5	0.1	0.2	0.3	0.5
12	−4.5	−7.2	−8.3	−10.0	24.8	25.7	26.5	27.0
24	−3.2	−6.2	−7.4	−8.8	23.1	24.2	25.3	26.0
48	−0.6	−3.7	−5.3	−7.4	22.0	23.1	23.7	25.1
72	1.2	−1.8	−3.6	−6.0	21.8	22.6	23.0	24.5
96	2.8	−0.3	−2.1	−4.6	22.5	22.5	22.5	23.8
120	4.1	1.0	−0.8	−3.5	22.8	22.4	22.2	23.5
Synthetic Profiles	−10.7	−10.4	−10.3	−10.0	32.0	30.8	30.3	29.9
GDEM Climatology	11.2	11.4	11.5	10.9	30.9	31.2	31.8	32.3
BT Climatology	−9.6	−7.8	−6.4	−4.8	28.7	28.2	28.0	28.5
MLD Climatology	4.8	7.0	7.5	7.7	25.1	26.2	27.2	28.6

hindcasts reduce the initial shallow MLD bias of the synthetic profiles from about 10 m to less than 5 m and reduce the rms error from 30–32 m to 22–23 m.

The MLD for the BT climatology is biased shallow, whereas the MLD climatology has a deep bias. In general, the MLD of mean temperature profiles that are calculated by averaging observed temperatures at specific depths tend to be biased shallow with respect to the mean observed MLD. This bias occurs because a few profiles with shallow MLDs can introduce sufficient stratification into the average profile that the MLD of the average profile is shallower than the mean MLD of the individual profiles. Table 2 shows a comparison of monthly values of the mean 0.2°C MLD at Victor (the MLD climatology) with the MLD derived from the mean monthly temperature profiles (the BT climatology). The MLD for the mean monthly temperature profiles is biased shallow relative to the mean MLD for every month of the year by an amount ranging from 6 to 31 m.

The MLD of the GDEM profiles shows a deep bias relative to the observed profiles. Because a main use of GDEM is to provide thermal and salinity structure for acoustic calculations, GDEM was purposely constructed to avoid underestimating the mean depth of the surface mixed layer and the surface sound-channel (Davis et al. 1986), and this is reflected in the GDEM MLDs in Table 2 and in the mean MLD error of GDEM in Table 1.

Table 3 shows the monthly mean and rms errors for the 0.2°C MLD for the 120-h hindcasts for the synthetic profiles and for the GDEM, BT, and MLD climatologies. The hindcast rms MLD error shows improvement over the synthetic error for most of the fall and winter months, but not for the period May through August. This improvement was somewhat surprising, since previous mixed-layer hindcasts generally showed more skill in spring and summer than in fall and winter Martin 1993; 1994b), including hindcasts at Victor (Martin 1994a).

Since the MLD of the synthetic profiles generally has a large, shallow bias with respect to the observed MLD in fall and winter (Table 3), the hindcast skill at this time could be attributed largely to the general deepening of the mixed layer from its initial value (provided by the synthetic profiles), which is caused by the surface cooling and stronger than average winds at this time of year. However, in January the shallow bias of the synthetic profiles does not seem sufficient to account for the improvement shown by the hindcast rms MLD error over the MLD error of the synthetic

Table 2 — Comparison of the Monthly Mean 0.2°C MLD at Victor. The MLD Values in the Table are in Meters

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of BTs	665	423	683	911	1173	1362	1156	1472	994	1062	1354	892
MLD Climatology	92	93	81	44	26	20	12	15	25	42	67	83
MLD of Monthly Mean T(z)	69	70	56	26	13	10	6	7	19	27	54	52
GDEM Climatology	107	97	104	50	21	24	14	15	29	38	68	86
Number of Deep BTs	66	56	70	144	163	125	162	155	93	96	156	57
Mean MLD of Deep BTs	84	101	85	47	14	12	6	9	16	28	52	70
Mean MLD of Synthetic BTs	79	83	81	31	14	11	8	7	8	8	19	36

Table 3 — Monthly Mean and rms 0.2°C MLD Errors at Victor for 120-h Hindcasts (Hind), for the Synthetic Profiles (Syn) from which the Hindcasts were Initialized, and for Three Climatologies of GDEM, BT, and MLD

		Mean MLD Error (m)					rms MLD Error (m)				
Month	Number	Hind	Syn	GDEM	BT Clim	MLD Clim	Hind	Syn	GDEM	BT Clim	MLD Clim
Jan	66	9.1	-4.9	19.4	-19.0	5.9	38.5	54.8	46.3	44.8	41.1
Feb	56	4.2	-18.2	36.2	-33.4	-9.9	46.3	66.3	68.2	67.3	59.2
Mar	70	8.0	-3.3	22.3	-36.4	-9.3	41.5	42.7	48.0	56.2	43.9
Apr	144	-0.6	-16.4	32.3	-19.1	3.3	31.6	39.6	49.8	43.2	38.3
May	163	1.8	0.2	26.4	-0.8	12.2	9.3	9.0	28.1	9.3	15.1
Jun	125	-2.1	-1.5	16.1	-2.3	7.1	10.1	9.3	19.1	10.1	12.3
Jul	162	3.4	2.4	12.2	1.1	7.0	6.9	5.6	13.5	5.3	8.7
Aug	155	3.5	-1.6	3.1	-2.0	5.4	7.9	5.6	6.4	5.8	7.8
Sep	93	2.6	-8.9	0.7	0.6	9.3	10.0	13.8	9.9	9.8	13.6
Oct	96	-5.0	-20.1	-3.9	-1.7	12.8	12.6	23.3	12.4	12.0	17.6
Nov	156	-5.4	-33.9	-15.9	-3.4	13.7	25.1	40.4	28.0	22.5	26.1
Dec	57	0.6	-33.5	-4.1	-15.9	11.3	20.4	44.6	22.6	29.3	26.0
Total	1343	1.0	-10.4	11.4	-7.8	7.0	22.4	30.8	31.2	28.2	26.2

profiles. An inspection of the individual hindcasts for January showed that on a number of occasions a modest (<10 m) shallowing of the mixed layer that improved the agreement of the hindcast MLD with the observed MLD appeared to occur; however, the shallowing was due to the mixing out of an inversion in the synthetic profiles that were used to initialize the hindcasts (Fig. 3). Hence, the apparent hindcast "skill" in these cases was due to a combination of a temperature inversion in the synthetic profile and the way in which MLD was defined. But the absence of strong winds and strong surface cooling on some of these occasions kept the hindcast mixed layer from deepening more than it did, which did help the agreement with the observed MLD.
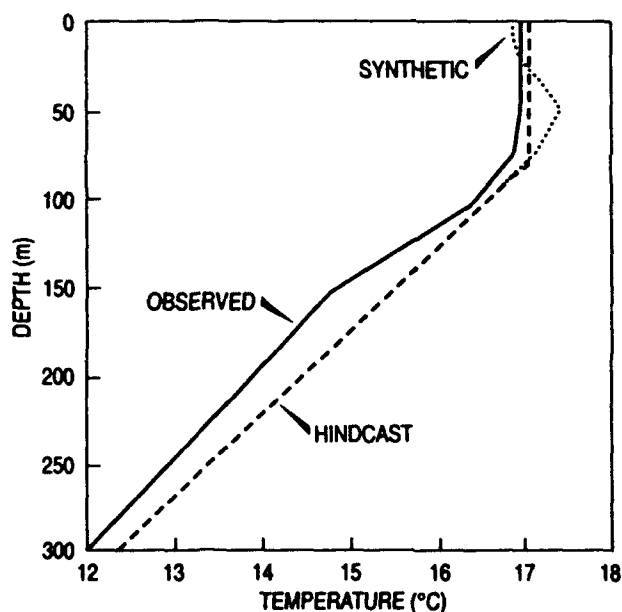

Figure 3. Observed, initial (synthetic), and hindcast temperature profiles for a hindcast conducted at Victor in January 1971. The synthetic profile used to initialize the hindcast shows an inversion in the upper 50 m. The inversion is eliminated by vertical mixing during the hindcast.

There is a general problem with hindcasting the MLD with a local mixed-layer model at middle and high latitudes in fall and winter with initialization from synthetic or climatological profiles. Because solar heating is weak and net surface cooling predominates, the hindcast can deepen a profile that is initially too shallow, but will not often shallow a profile that is initially too deep. For example, of the 335 hindcasts conducted at Victor between November and February (Table 3), only two resulted in a final mixed layer significantly shallower than that of the initial profile. The hindcasts conducted in this study show skill relative to the synthetic profiles in fall and winter primarily because the synthetic profiles tend to be biased shallow. If the MLD of the initial profiles had a zero bias or had been biased deep, the rms MLD error of the hindcasts would most likely have been greater than that of the initial profiles.

To try to determine why the hindcast MLDs were showing no improvement over the MLDs of the synthetic profiles in the summer, the summer hindcasts were inspected in more detail. Figures 4 and 5 show scatter plots of windspeed versus MLD for the observed, synthetic, and hindcast temperature profiles for the months of June and July. The windspeed in these plots is the average windspeed for the 4 h preceding the time the observed profiles were taken (i.e., the average

Figure 4. Scatter plots of windspeed vs. MLD for (a) observed, (b) synthetic, and (c) hindcast profiles for hindcasts conducted at Victor during June. The windspeed is an average over the last 4 h of the hindcasts.
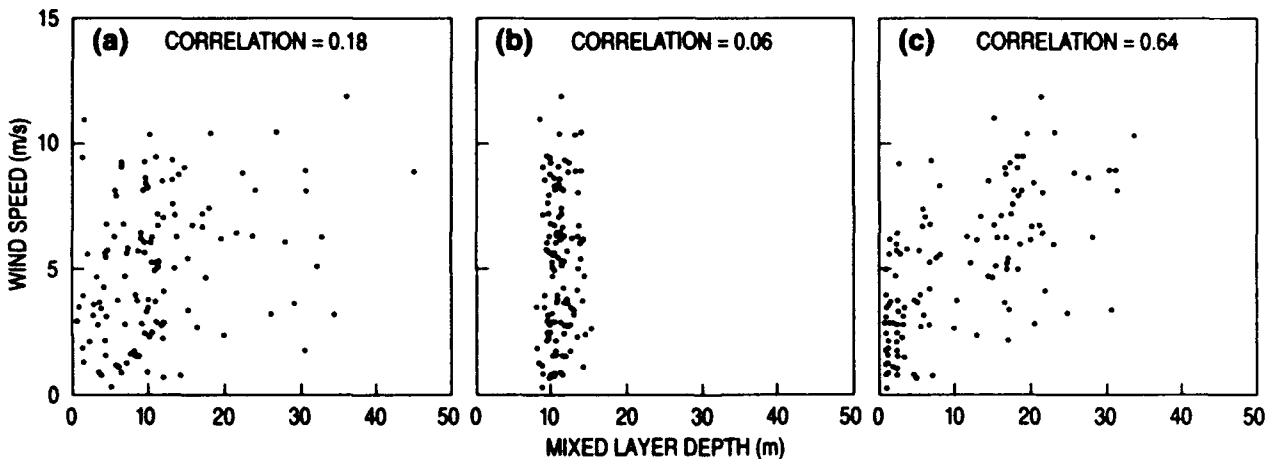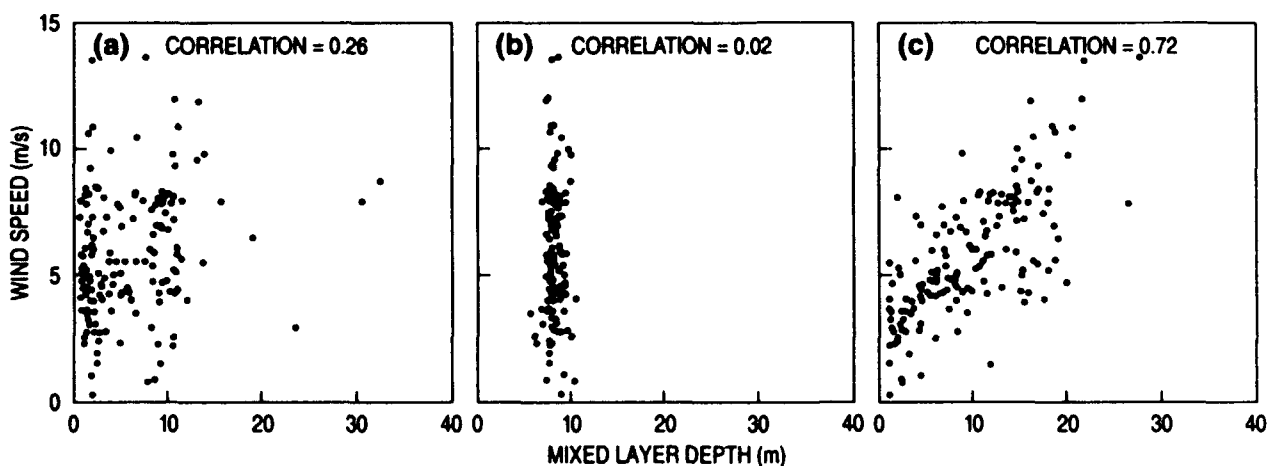

Figure 5. Scatter plots of windspeed vs. MLD for (a) observed, (b) synthetic, and (c) hindcast profiles for hindcasts conducted at Victor during July. The windspeed is an average over the last 4 h of the hindcasts.

windspeed over the last 4 h of the hindcasts). Calculations in which the windspeed was averaged over the last hour or last 24 h of the hindcasts did not give substantially different results. Although MLD depends on factors other than the recent windspeed, the MLD should have some correlation with the windspeed at this time of year.

For the synthetic profiles, the MLDs fall in a narrow range, and the correlation between the MLD and the windspeed is very low: 0.06 and 0.02 for June and July, respectively.

The correlation between the windspeed and the MLD for the hindcast profiles is 0.64 and 0.72 for June and July. However, for the observed profiles, the correlation is only 0.18 and 0.26. This correlation is at least positive, but is fairly weak. Figures 6 and 7 show plots of hindcast versus observed MLD, where the size of the circle representing each point has been drawn proportional to the magnitude of the windspeed (the smallest circles correspond to windspeeds near zero, and the largest correspond to windspeeds of about 13 m/s). The largest discrepancies occur when the hindcast MLD is very low and the observed MLD is very high and vice versa. In most of these cases, the observed windspeed is more consistent with the hindcast value of the MLD than the observed value. For example, in June there are several cases where the hindcast MLD is very small and is much less than the observed MLD, and the winds are very light. In July, there are a number of cases where the hindcast MLD is much larger than the observed MLD, and the winds appear to have been sufficiently high to have mixed the surface layer deeper than indicated by the MLD derived from the observed temperature profile.

These discrepancies must be due either to advective effects at Victor, or to inaccuracies in the observed temperature profiles or atmospheric forcing. Errors in the temperature profiles seems a likely cause of the discrepancies, since small errors in the temperature profiles can significantly

Figure 6. Plot of hindcast MLD vs. observed MLD for hindcasts conducted at Victor during June. The size of the circles is proportional to the mean value of the winds ~eed over the last 4 h of the hindcasts. The range of the wind-speed values is 0 to 12 m/s.
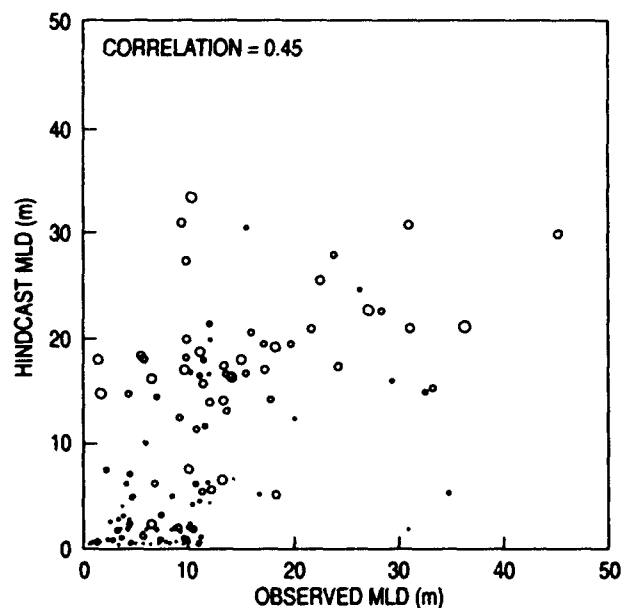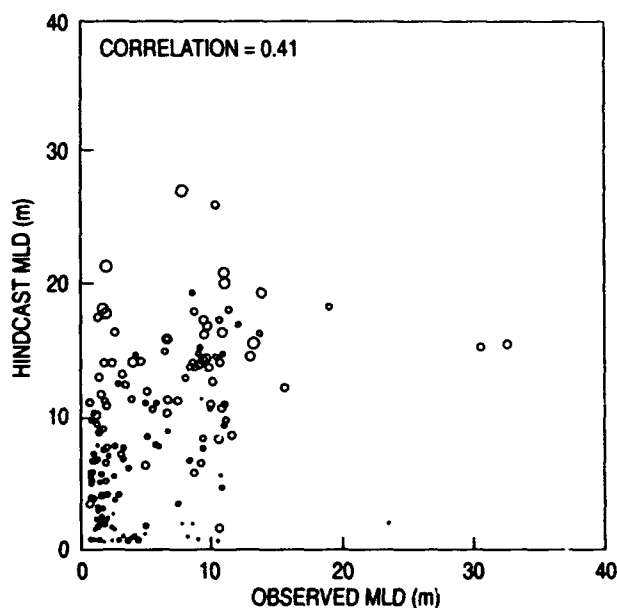
Figure 7. Plot of hindcast MLD vs. observed MLD for hindcasts conducted at Victor during July. The size of the circles is proportional to the mean value of the windspeed over the last 4 h of the hindcasts. The range of the wind-speed values is 0 to 14 m/s.
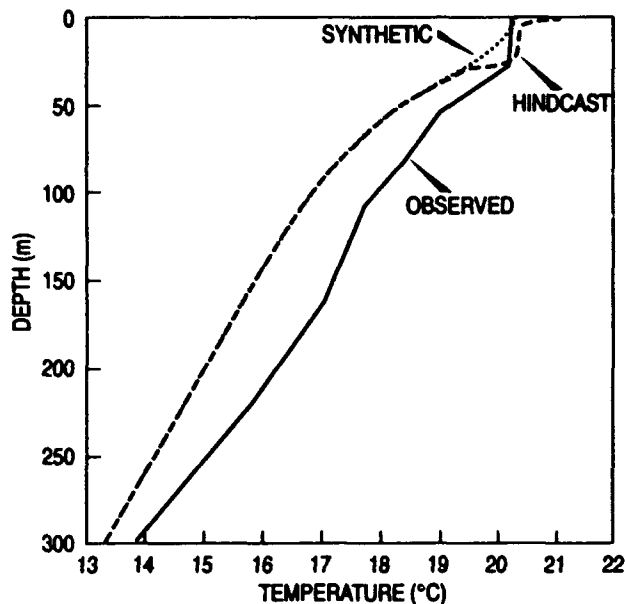
Figure 8. Observed, initial (synthetic), and hindcast temperature profiles for a hindcast conducted at Victor in June 1968. The hindcast temperature profile shows a shallow mixed layer of about 2-m depth caused by strong heating and light winds that does not appear in the observed profile.

affect the calculated MLD. For example, in June there are several occurrences in the hindcasts of warm, shallow, mixed layers of 1- or 2-m depth caused by strong heating and very light winds that are not reflected in the observed temperature profiles. Since the warm surface layer occurs in the upper 1 or 2 m (Fig. 8), it may not have been recorded in the observed temperature profile. Such discrepancies between the hindcast and the observed MLDs contribute significantly to the overall rms hindcast error. In a frontal area, such as the Kuroshio Extension, horizontal temperature gradients can be high, and there is the possibility that some of the discrepancies could be due to advective effects. Not much is known about the effects of advection on the MLD in strong frontal regions.

B. Hindcast Experiments at Victor with Deep Profiles Spliced to MBT Profiles

Previous hindcast experiments at Victor by Martin (1994a) primarily used the MBT data from Victor, which were taken much more frequently than the deep profiles. It was considered that the MBT data might yield more accurate values of MLD than the deep profiles. The depths of the MBTs are limited to less than 300 m, but since the MBT temperatures are recorded every 5 m, they can potentially provide good spatial resolution of the thermal structure near the surface.

Since the MBTs do not extend below 300-m depth, deep (>1000 m) temperature profiles were spliced onto the bottom of the MBTs to obtain deep profiles for calculating synthetic profiles. The deep profiles were exponentially merged to the bottom of the MBTs with an e-folding depth of 300 m. An MBT was merged with a deep profile only if it was taken within 1 d and within 25 km of the deep profile (if there was a choice of several MBTs, the one closest in time to the deep profile was used). Since MBTs that met this criteria were not always found, the total number of observed profiles that were obtained was reduced from the 1343 profiles used in the previous section to 769.

The mixed-layer hindcasts were conducted as described in the previous section. The time assigned to the observed profiles was that of the MBT, since the MLD used to validate the hindcasts was provided by the MBT.

Table 4 shows a comparison of the annual mean and rms MLD errors for the hindcasts with the MLD errors for the synthetic profiles, and the GDEM, BT, and MLD climatologies. Table 5 shows the monthly errors for the 0.2°C MLD. The mean MLD of the MBTs used to validate these hindcasts is significantly deeper than the mean MLD of the deep profiles used in the previous section. The mean MLD of the MBTs is greater than the mean MLD of the deep profiles for almost every month, as well as over the whole year (Table 6). Since the observed MLD is generally deeper, the shallow MLD bias of the synthetic profiles and the BT climatology is increased, the deep bias of GDEM and the MLD climatology is reduced, and the shallow bias of the hindcast profiles is increased from that of the experiment reported in the previous section (compare Tables 4 and 5 with Tables 1 and 3).

The rms MLD errors for both the hindcast and synthetic temperature profiles are higher than for the previous experiment. For the most part, this higher error reflects the increase in the mean error (bias). The overall skill of the hindcasts (the improvement of the hindcast rms MLD error over the rms MLD error of the synthetic profiles) is about the same as before. On a monthly basis, the hindcasts with the MBT data more consistently show skill over the synthetic profiles; however, this is largely due to increase in the MLD bias of the synthetic profiles relative to the observed profiles in the spring and summer.

C. Correction of the SST of Hindcast Profiles

The synthetic profiles used in operational analyses are determined from SSH and/or SST. If an observed or estimated SST is available, it is desirable that the synthetic profile or the hindcast profile derived from the synthetic profile have an SST that agrees with the specified (observed or estimated) SST. In the algorithms currently being used within MODAS to generate the synthetic

Table 4 — Comparison of the Mean and rms MLD Error for 12- to 120-h Mixed-Layer Hindcasts, with the MLD Error of Synthetic Profiles Used to Initialize the Mixed-Layer Hindcasts and with the Error of the GDEM, BT, and MLD Climatologies. The MLD Errors are Calculated Based on the Observed MLDs of the MBT Profiles that were Merged to the Observed Deep Temperature Profiles.

	Mean MLD Error (m)				rms MLD Error (m)			
	MLD Criteria (°C)							
Hindcast Duration (h)	0.1	0.2	0.3	0.5	0.1	0.2	0.3	0.5
12	−13.9	−16.5	−17.1	−16.0	31.5	33.8	33.5	31.5
24	−12.2	−15.3	−16.2	−16.0	29.6	31.8	31.8	30.3
48	−9.7	−13.1	−14.1	−14.4	28.1	29.8	29.8	29.1
72	−8.0	−11.2	−12.4	−12.9	27.8	28.7	28.6	28.1
96	−6.6	−9.8	−11.0	−11.7	27.7	28.2	27.7	27.2
120	−5.4	−8.5	−9.7	−10.5	27.5	27.7	27.1	26.4
Synthetic Profiles	−20.2	−19.6	−18.6	−16.6	36.2	36.3	34.6	32.9
GDEM Climatology	1.9	2.2	2.9	3.9	29.9	29.5	29.4	29.3
BT Climatology	−19.8	−18.2	−16.2	−13.2	34.0	32.5	30.7	28.5
MLD Climatology	−5.5	−3.4	−2.3	−0.5	25.4	24.6	24.6	24.8

Table 5 — Monthly Mean and rms 0.2°C MLD Errors for 120-h Hindcasts for the Synthetic Profiles from which the Hindcasts were Initialized, and for Three Climatologies: GDEM, BT, and MLD. The MLD Errors are Calculated Based on the MLDs of the Observed Profiles.

		Mean MLD Error (m)					rms MLD Error (m)				
Month	Number	Hind	Syn	GDEM	BT Clim	MLD Clim	Hind	Syn	GDEM	BT Clim	MLD Clim
Jan	45	−14.7	−32.3	−6.0	−43.4	−17.8	37.2	64.2	41.8	58.1	44.8
Feb	26	14.4	−12.9	39.4	−29.6	−6.0	43.2	56.2	59.5	50.0	35.7
Mar	31	−7.5	−25.6	5.3	−53.1	−26.5	50.8	59.8	46.5	79.4	58.4
Apr	91	−4.4	−16.7	26.3	−23.9	−2.0	48.1	41.7	44.4	42.3	34.4
May	102	−5.7	−7.7	19.3	−8.1	4.9	13.3	15.1	23.1	16.4	13.0
Jun	100	−13.0	−12.8	5.2	−13.6	−4.1	19.6	19.1	16.4	21.3	16.7
Jul	80	−4.8	−5.6	3.6	−7.1	−1.2	8.9	8.9	8.2	9.8	6.9
Aug	93	−0.7	−7.9	−3.3	−8.5	−1.1	8.6	10.5	7.9	11.0	7.0
Sep	53	−9.9	−21.3	−12.1	−12.2	−3.6	15.2	24.6	16.5	20.1	13.2
Oct	44	−14.3	−30.1	−13.7	−11.5	3.3	18.3	33.4	19.8	19.9	14.6
Nov	61	−23.2	−50.1	−32.7	−21.3	−3.4	28.0	51.5	35.1	29.2	17.2
Dec	43	−17.2	−52.3	−19.0	−32.0	−4.3	60.9	31.4	33.7	53.2	37.7
Total	769	−8.5	−19.6	2.2	−18.2	−3.4	27.7	36.3	29.5	34.0	25.4

Table 6 — Comparison of Monthly Mean 0.2°C MLD for Deep Temperature Profiles Used for Hindcasts at Victor in Sec. II A, with the Monthly Mean 0.2°C MLD of the MBTs Used for Hindcasts in Sec. II B

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of Deep BTs	66	56	70	144	163	125	162	155	93	96	156	57
Mean MLD of Deep BTs	84	101	85	47	14	12	6	9	16	28	52	70
Mean MLD of MBTs	110	97	104	50	21	24	14	15	29	38	68	86
Number of MBTs	45	26	31	91	102	100	80	93	53	44	61	43

profiles, the SST of a synthetic profile may not be quite the same as the specified SST, although it is usually close, i.e., within 1°C. (This discrepancy is being eliminated in changes to MODAS that are presently being implemented—Mike Carnes, NRL, personal communication.) If the synthetic profile is hindcast, of course, the SST is further modified. Table 7 shows monthly values of the mean and rms SST error for the synthetic profiles and for the 120-h hindcasts discussed in Sec. II. A. As would be expected, the hindcasts show the largest SST errors in the summer when light winds and strong heating can cause large changes in SST over short periods. In June and July, the rms error of the hindcast SST is about 1°C.

There are various ways the SST error of the hindcasts could be corrected. One straightforward method is to perform the hindcast, calculate the SST error, and then recalculate the synthetic profile with a specified SST modified by the change expected during the hindcast. Then the hindcast can be repeated, and the SST of the hindcast temperature profile should then be close to the observed

Table 7 — Monthly Mean and rms SST Error for Synthetic Profiles Used to Initialize Hindcasts at Victor and for 120-h Hindcasts

Month	Number BTs	Mean SST Error (°C)		rms SST Error (°C)	
		Syn	Hind	Syn	Hind
Jan	66	−0.05	−0.16	0.13	0.24
Feb	56	−0.06	−0.23	0.08	0.29
Mar	70	−0.07	−0.17	0.07	0.22
Apr	144	0.03	0.07	0.09	0.43
May	163	−0.17	0.34	0.21	0.62
Jun	125	−0.27	0.60	0.38	1.02
Jul	162	−0.56	0.43	0.63	0.95
Aug	155	−0.30	−0.03	0.48	0.76
Sep	93	0.33	−0.21	0.38	0.63
Oct	96	0.62	−0.26	0.63	0.57
Nov	156	0.30	−0.49	0.32	0.55
Dec	57	0.13	−0.46	0.15	0.50
Total	1343	−0.04	0.02	0.38	0.67

Table 8 — Monthly Mean and rms SST Error for Synthetic Profiles and for 120-h Hindcasts in which the Initial Profile was Adjusted for the Expected Change in SST During the Hindcast

Month	Number BTs	Mean SST Error (°C)		rms SST Error (°C)	
		Syn	Hind	Syn	Hind
Jan	66	−0.05	−0.01	0.13	0.02
Feb	56	−0.06	−0.01	0.08	0.02
Mar	70	−0.07	−0.01	0.07	0.02
Apr	144	0.03	0.00	0.09	0.02
May	163	−0.17	0.01	0.21	0.03
Jun	125	−0.27	0.04	0.38	0.11
Jul	162	−0.56	0.02	0.63	0.07
Aug	155	−0.30	−0.01	0.48	0.07
Sep	93	0.33	−0.01	0.38	0.05
Oct	96	0.62	0.01	0.63	0.03
Nov	156	0.30	−0.02	0.32	0.04
Dec	57	0.13	−0.04	0.15	0.05
Total	1343	−0.04	0.00	0.38	0.06

value. (Note that this method provides a correction for any error in the SST of the initial synthetic profile, as well as the SST change during the hindcast.) Since the initial profile for the hindcast is changed, the SST change during the hindcast could be affected. However, because the change in the SST specified in recalculating the synthetic profile is small, the near-surface stratification of the synthetic profile should be similar to that of the initial synthetic profile, and the SST change during the second hindcast should be similar to the change during the initial hindcast.

Table 8 shows monthly mean and rms SST errors for 120-h hindcasts in which the SSTs of the synthetic profiles used to initialize the hindcasts were adjusted for the expected change in SST during the hindcasts. (Note that the synthetic SST error in Table 8 is the SST error for the original, not the adjusted, synthetic profiles.) Compared to using the unadjusted synthetic profiles for initialization (Table 7), the monthly mean SST error is reduced from a maximum of 0.60°C to 0.04°C, and the monthly rms SST error is reduced from a maximum of 1.02°C to 0.11°C. The total rms error for all the hindcasts is reduced from 0.67°C to 0.06°C. Table 9 shows the monthly mean and rms 0.2°C MLD errors for the hindcasts in which the SST was corrected. Comparison of Table 9 with Table 3 shows that the corrected SST has little overall effect on the MLD error.

III. HINDCASTS WITH NOGAPS ATMOSPHERIC FORCING AND GLOBAL BTs

As noted earlier, most of the hindcast studies that have been conducted to date have used local meteorological observations to calculate atmospheric forcing. However, the operational

Table 9 — Monthly Mean and rms 0.2°C MLD Error for Synthetic Profiles and for 120-h Hindcasts in which the Initial Profile was Adjusted for the Expected Change in SST During the Hindcast

Month	Number BTs	Mean MLD Error (m)		rms MLD Error (m)	
		Syn	Hind	Syn	Hind
Jan	66	−4.9	7.5	54.8	38.8
Feb	56	−18.1	1.2	66.3	46.8
Mar	70	−3.3	5.7	42.7	41.1
Apr	144	−16.4	−2.0	39.6	30.9
May	163	0.2	1.8	9.0	9.3
Jun	125	−1.5	−2.2	9.3	10.1
Jul	162	2.4	3.4	5.6	6.9
Aug	155	−1.6	3.4	5.6	7.8
Sep	93	−8.9	2.5	13.8	9.9
Oct	96	−20.1	−5.3	23.3	12.7
Nov	156	−33.9	−7.4	40.4	25.0
Dec	57	−33.5	−4.5	44.6	22.1
Total	1343	−10.3	0.1	30.8	22.4

mixed-layer hindcasts that are conducted at FNMOC and NAVOCEANO use atmospheric forcing from the Navy operational atmospheric models. Since we expect that atmospheric forcing from large-scale atmospheric models might be less accurate than atmospheric forcing calculated from local meteorological observations, there is the question of how much skill mixed-layer hindcasts that are forced by wind stress and heat flux fields from the operational atmosphe   models will have in predicting MLD.

To investigate this question, hindcasts were initialized from GDEM temperature and salini y profiles, forced with wind stresses and heat fluxes from NOGAPS, and validated against observed temperature profiles. BTs and atmospheric forcing fields from NOGAPS were acquired ior April through September of 1990. The study was confined to the spring and summer months (for the northern hemisphere), since it was expected that hindcasts initialized from climatology would show more skill in predicting MLD in spring and summer than in fall and winter.

For each observed BT, GDEM temperature and salinity profiles were obtained for the location and day of the BT observation with software developed by DART. A time series of wind stress, effective cloud cover (used for the calculation of solar radiation), and surface heat flux were extracted from the 1990 global NOGAPS fields at the location of each observed BT for a period extending from at least 5 d before the time of the BT to just after the BT was taken. The NOGAPS fields that were used have a temporal resolution of 6 h and a spatial resolution of 2.5°.

A special procedure was used to interpolate the NOGAPS solar radiation fields. Because of the diurnal variability of solar radiation, the 6-h NOGAPS solar radiation values could not be interpolated directly. Instead, each NOGAPS solar radiation value was converted to an effective "cloud factor" by dividing by the solar radiation expected at that time and location for typical clear-sky conditions. The clear-sky values were calculated with the Fritz formula (List 1958). The 6-h cloud factors were then interpolated to the location of the mixed-layer hindcasts, and during the hindcasts were interpolated in time to provide attenuation of the diurnally varying radiation calculated with the Fritz formula for clear skies. The Jerlov Type IA extinction profile (Jerlov 1968) was used to describe the attenuation of solar radiation with depth.

The hindcasts were conducted for durations of 12 to 120 h in the same manner as the hindcasts at Victor (Sec. II). For example, for hindcasts of 72-h duration, each individual hindcast was initialized 72 h before its respective BT observation was taken and was hindcast up to the time of the BT observation. For each hindcast, the MLD of the initial GDEM temperature profile and the MLD of the hindcast temperature profile were compared with the MLD derived from the observed temperature profile. Mean and rms MLD errors were calculated for GDEM and for the hindcasts on an overall and monthly basis.

Since the near-surface stratification and MLD tend to adjust to the atmospheric forcing during the heating season in spring and summer, the hindcast MLDs should, on average, show some skill relative to the climatological MLDs if the atmospheric forcing and the observed MLDs are sufficiently accurate. However, because the hindcasts are initialized from climatology, there is little reason to expect much skill in hindcasting actual temperature values.

The Price mixed-layer model was used for the hindcasts. The model integrations were conducted on a stretched vertical grid with a resolution of 1 m at the surface, a 6% increase in the thickness of each successive layer with depth, and a maximum depth of 300 m. The model timestep was 600 s.

As noted earlier, the accuracy of the MLDs calculated from the observed BTs is crucial to getting a valid estimate of the hindcast error for this experiment. Hence, some coarse checks were conducted on the observed BTs to eliminate suspect and unsuitable profiles. Profiles that did not start within 5 m of the surface; that were less than 50 m deep; that had less than a 1°C temperature drop from top to bottom; that contained near-surface temperature inversions, such that the SST was exceeded by more than 0.2°C; and that deviated more than 8°C from GDEM were thrown out. Additionally, BTs within 5° of the equator and BTs for which GDEM profiles could not be obtained were discarded. After these checks, 9141 of the original 13,243 BTs were retained. Figure 9 shows the global distribution of these BTs.

Table 10 provides a summary of the mean and rms MLD errors for hindcasts of 12- to 120-h duration. Results are presented for several definitions of MLD, i.e., for MLDs defined as the depth at which the temperature is 0.1, 0.2, 0.3, and 0.5°C less than the SST. Results are shown for all the BTs and for three selected regions: the northwest and northeast Pacific and the North Atlantic between 20 and 50° N. The hindcast skill in Table 10 is defined as the percent improvement of the hindcast rms error over the GDEM rms error.
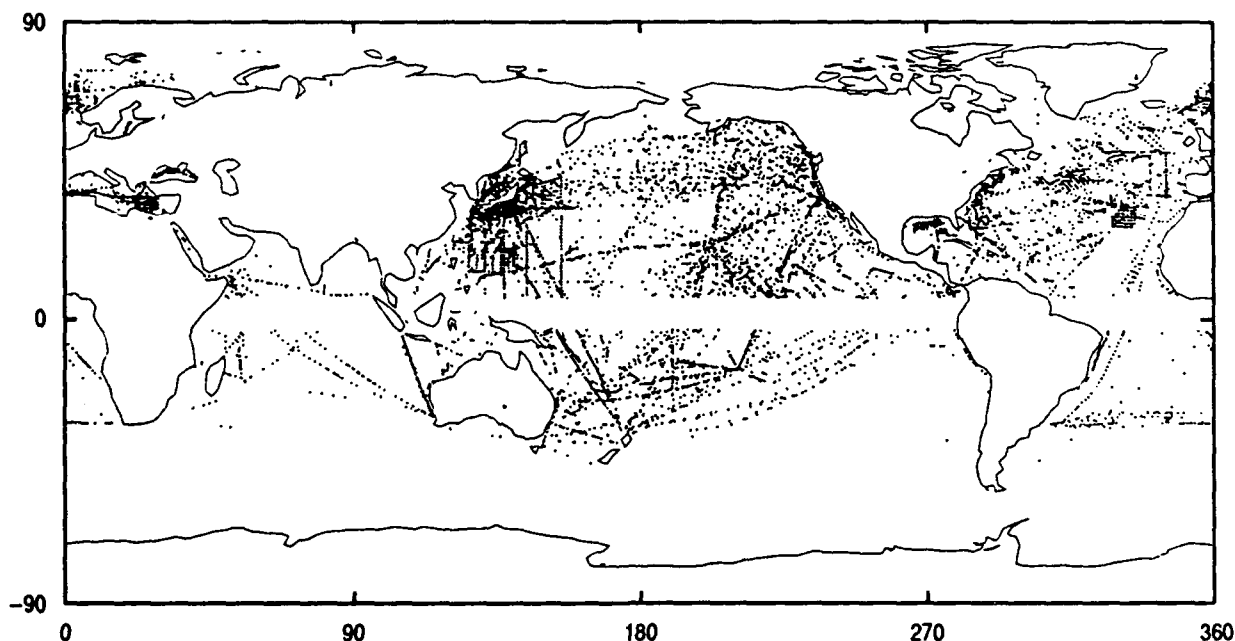

Figure 9. Global distribution of BTs taken between April and September 1990 that were used for mixed-layer hindcast experiments with NOGAPS atmospheric forcing

Table 10 — Comparison of the Mean and rms MLD Error for 12- to 120-h Mixed-Layer
Hindcasts with the MLD Error for the GDEM Temperature Profiles with which the Hindcasts
were Initialized. The GDEM and Hindcast MLD Errors were Calculated Relative to the
MLD of the Observed Temperature Profiles. Hindcast Skill is Defined as the Percent
Improvement of the Hindcast rms Error Over the GDEM rms Error. Results are Shown
for All the BTs, and for Some Selected Regions.

Hindcast Duration (h)	Mean MLD Error (m)				rms MLD Error (m)				Hindcast Skill			
	MLD Criteria (°C)											
	0.1	0.2	0.3	0.5	0.1	0.2	0.3	0.5	0.1	0.2	0.3	0.5
All BTs (9141 BTs)												
GDEM	8.4	8.1	8.4	8.7	25.7	27.4	28.7	31.4				
12	8.1	7.1	7.3	7.8	24.7	26.1	27.6	30.6	4%	5%	4%	2%
24	8.2	7.2	7.3	7.8	24.9	26.1	27.5	30.4	3%	5%	4%	3%
48	9.3	7.8	7.4	7.6	25.5	26.0	27.2	30.0	1%	5%	5%	4%
72	10.0	8.3	7.8	7.7	26.1	26.2	27.1	29.7	-2%	4%	6%	5%
120	10.0	8.3	7.8	7.7	26.1	26.2	27.1	29.7	-2%	4%	6%	5%
Northwest Pacific (120–190° E, 20–50° N, 2036 BTs)												
GDEM	7.3	7.7	7.8	7.5	18.6	20.8	23.2	26.5				
12	8.9	8.0	7.6	7.2	18.7	20.3	22.5	26.0	-1%	3%	3%	2%
24	8.8	8.0	7.5	7.1	19.1	20.7	22.6	25.8	-3%	1%	2%	3%
48	9.6	8.4	7.5	6.9	20.0	20.9	22.6	25.5	-8%	0%	3%	4%
72	10.1	8.9	8.0	7.1	20.5	21.3	22.8	25.4	-10%	-2%	2%	4%
120	10.1	8.9	8.0	7.1	20.5	21.3	22.8	25.4	-10%	-2%	2%	4%
Northeast Pacific (190–260° E, 20–50° N, 1108 BTs)												
GDEM	14.8	16.2	17.8	18.9	24.5	27.4	29.9	33.4				
12	12.2	12.8	14.1	16.1	22.6	24.7	27.2	31.5	8%	10%	9%	6%
24	10.5	11.4	13.1	15.4	21.2	23.4	26.2	30.9	13%	15%	12%	7%
48	10.9	11.0	11.9	13.6	21.4	22.9	25.4	30.3	13%	16%	15%	9%
72	10.6	10.7	11.3	12.4	21.3	22.5	24.9	29.9	13%	18%	17%	11%
120	10.6	10.7	11.3	12.4	21.3	22.5	24.9	29.9	13%	18%	17%	11%
North Atlantic (280–355° E, 20–50° N, 1287 BTs)												
GDEM	13.4	14.3	15.1	16.2	31.8	36.2	38.9	44.1				
12	10.9	11.1	11.9	13.5	29.6	33.8	37.1	42.8	7%	6%	5%	3%
24	10.1	10.4	11.3	12.9	29.3	33.1	36.4	42.1	8%	9%	6%	4%
48	9.8	9.0	9.6	11.4	28.9	31.6	34.5	40.4	9%	13%	11%	8%
72	9.7	8.5	8.8	10.4	29.1	30.8	33.3	38.9	9%	15%	14%	12%
120	9.7	8.5	8.8	10.4	29.1	30.8	33.3	38.9	9%	15%	14%	12%

The mean MLD errors in Table 10 show a consistent deep bias for GDEM relative to the BT
observations. The deep bias is about 8 m overall in the northwest Pacific, and is 13 to 19 m in the
northeast Pacific and the North Atlantic. This is consistent with the deep bias shown by GDEM at
Victor (Table 1). The 72-h or longer hindcasts reduced the GDEM MLD bias in the northeast
Pacific and the North Atlantic by 4 to 7 m, but do not significantly improve the bias overall or
in the northwest Pacific. The rms errors and hindcast skill largely reflect the mean errors. The
overall hindcast skill is only about 4%, and the hindcasts in the northwest Pacific show little skill.
However, in the northeast Pacific and North Atlantic the hindcast skill is 9% to 18% for 72-h or
longer hindcasts. Higher skill in hindcasting the mixed layer in the northeast Pacific than in the

Table 11 — Mean and rms MLD Errors for GDEM and for Mixed-Layer Hindcasts of 72-h Duration for 20°-Wide Latitude Bands. The GDEM and Hindcast MLD Errors were Calculated Relative to the MLD of the Observed Temperature Profiles. Hindcast Skill is Defined as the Percent Improvement of the Hindcast rms Error Over the GDEM rms Error.

	Mean MLD Error (m)				rms MLD Error (m)				Hindcast Skill			
	MLD Criteria (°C)											
	0.1	0.2	0.3	0.5	0.1	0.2	0.3	0.5	0.1	0.2	0.3	0.5
	−40° to −20° N, 673 BTs											
GDEM	1.9	−1.2	−1.8	−2.0	36.6	38.0	38.4	38.3				
Hindcast	11.2	6.3	4.3	2.4	38.1	37.1	37.5	37.8	−4%	2%	2%	1%
	−20° to 0° N, 888 BTs											
GDEM	4.9	3.1	2.9	3.7	32.0	30.1	29.0	26.3				
Hindcast	5.0	2.9	2.5	3.5	31.0	28.9	28.1	25.7	3%	4%	3%	2%
	0° to 20° N, 1511 BTs											
GDEM	10.2	8.5	8.2	7.7	25.9	25.9	26.2	25.4				
Hindcast	8.2	5.6	5.2	5.1	25.9	25.3	25.5	24.8	0%	2%	2%	2%
	20° to 40° N, 3627 BTs											
GDEM	9.5	9.6	9.7	9.2	21.4	23.7	25.8	28.6				
Hindcast	8.1	6.6	5.9	5.3	19.9	21.4	23.3	26.4	7%	9%	10%	8%
	40° to 60° N, 2047 BTs											
GDEM	9.2	10.7	12.0	13.6	26.3	30.3	32.8	39.8				
Hindcast	14.8	14.3	14.4	15.1	28.3	28.8	30.3	36.7	−7%	5%	8%	8%
	60° to 80° N, 386 BTs											
GDEM	5.4	7.4	9.0	11.7	16.4	18.0	19.5	23.0				
Hindcast	19.6	19.1	18.7	18.7	25.9	25.0	25.0	27.1	−58%	−38%	−28%	−18%

northwest Pacific has also been noted with the Thermal Ocean Prediction System (TOPS) at FNMOC (Mike Clancy, FNMOC, personal communication). This skill has been attributed to the weaker advective effects and more dominant role of atmospheric forcing in modifying the upper ocean in the northeast Pacific.

Table 11 shows mean and rms MLD errors for GDEM and for 72-h hindcasts calculated for 20° latitude bands. Hindcast skill is marginal below 20° N, is highest in the middle latitudes at 20° to 60° N, and is really poor above 60° N where the hindcasts have a large, deep MLD bias.

Investigation of the hindcasts above 60° N showed that almost all of these were in the area of the Greenland-Iceland-Norwegian (GIN) Sea. Many of these hindcasts show a significant improvement over the initial GDEM profile in terms of their agreement with the observed MLD and near-surface stratification. Figure 10 shows a case where the hindcast mixed layer shallowed, and Fig. 11 shows a case where the hindcast mixed layer deepened; both cases resulted in good agreement with the observed MLD. However, a large number of the hindcasts show a deeper surface mixed layer than the observed profiles. In some of these cases the observed profiles indicate more near-surface stratification than the hindcast profiles (e.g., Fig. 12), which could be due to an error in the NOGAPS forcing (i.e., wind stress too strong and/or too much surface cooling) or to advection. In many other cases, the observed profile shows a much shallower thermocline than the hindcast profile, which suggests a shift in the position of the main fronts in the GIN Sea at this time relative to the location of the fronts in GDEM. Figure 13 shows an example of such a case that occurred
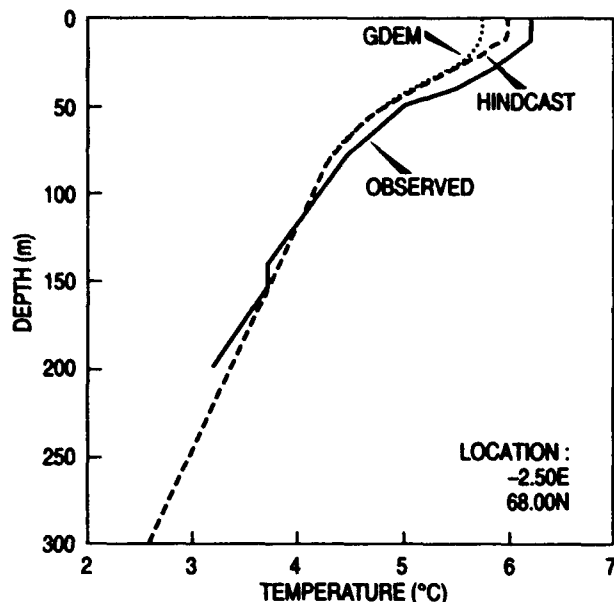
Figure 10. Observed, initial (GDEM), and hindcast temperature profiles for a hindcast conducted in the GIN Sea in June 1990. The hindcast temperature profile shows a shallowing of the mixed layer from its initial value caused by surface heating and light winds. The hindcast MLD agrees well with the observed MLD.
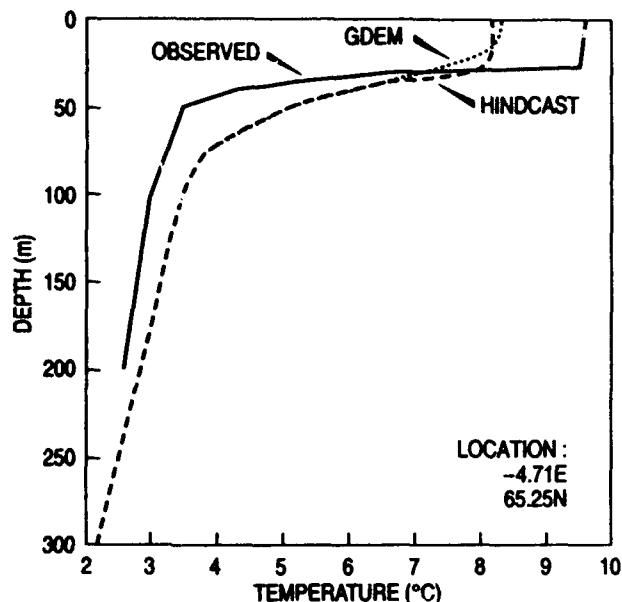
Figure 11. Observed, initial (GDEM), and hindcast temperature profiles for a hindcast conducted in the GIN Sea in July 1990. The hindcast temperature profile shows a deepening of the mixed layer from its initial value caused by wind mixing. The hindcast MLD agrees well with the observed MLD.
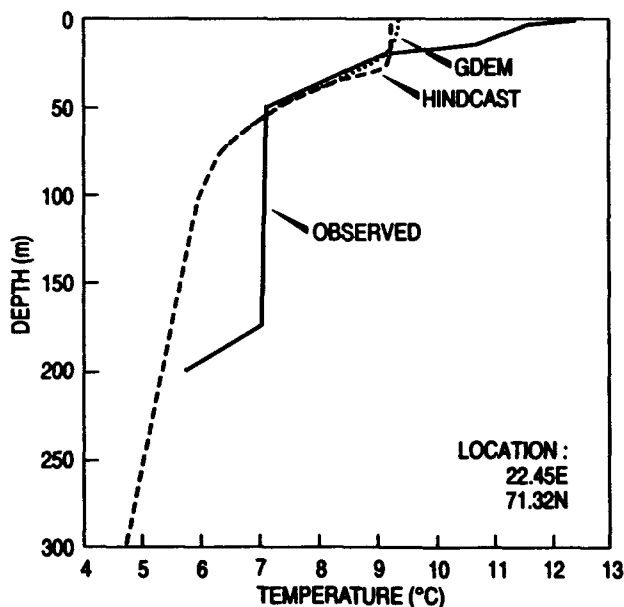
Figure 12. Observed, initial (GDEM), and hindcast temperature profiles for a hindcast conducted in the GIN Sea in August 1990. The hindcast temperature profile shows a deepening of the mixed layer from its initial value of about 20 m to about 30 m caused by wind mixing. This is in contrast to the observed temperature profile, which shows very high stratification between the surface and 20-m depth.
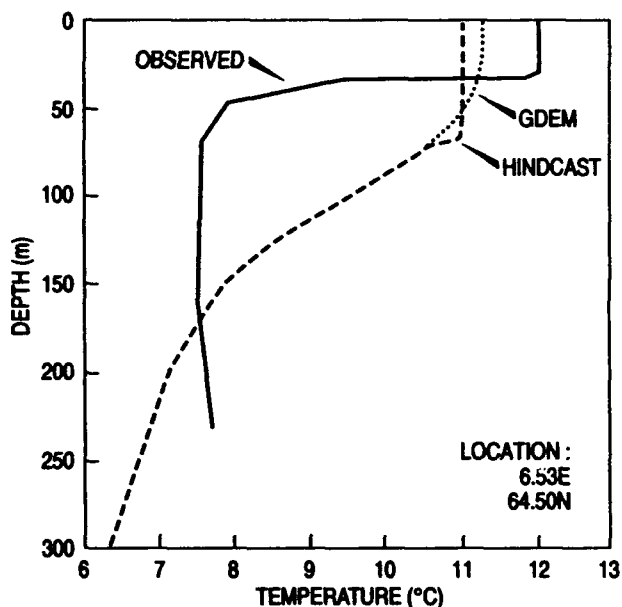
Figure 13. Observed, initial (GDEM), and hindcast temperature profiles for a hindcast conducted in the GIN Sea in September 1990. The initial (GDEM) temperature profile shows a much deeper thermocline than the observed temperature profile. Because of this, the deepening of the mixed layer during the hindcast, which is caused by wind mixing and surface cooling, results in an MLD that is much deeper than the observed MLD.

Table 12 — Monthly Variation of Mean and rms MLD Error for GDEM and for 72-h Mixed-Layer Hindcasts Initialized from GDEM. Calculation is for Midlatitudes (20–50° N). Hindcast Skill is Defined as the Percent Improvement of the Hindcast rms Error Over the GDEM rms Error.

Month	Number BTs	Mean MLD Error (m)		rms MLD Error(m)		Skill
		GDEM	Hindcast	GDEM	Hindcast	
MLD Criteria = 0.1°C						
Apr	776	21.60	19.78	39.12	38.34	2.0%
May	925	12.20	10.35	28.40	26.89	5.3%
Jun	886	11.53	10.02	18.65	16.91	9.3%
Jul	950	7.77	7.56	14.06	12.69	9.7%
Aug	827	4.09	5.14	15.04	14.61	2.9%
Sep	822	3.57	6.11	15.43	16.81	−8.9%
Total	5186	10.02	9.69	23.29	22.50	3.4%
MLD Criteria = 0.2°C						
Apr	776	23.00	18.73	44.45	39.83	10.4%
May	925	13.04	9.90	31.77	28.37	10.7%
Jun	886	12.69	9.51	22.62	19.92	11.9%
Jul	950	8.94	6.80	16.12	13.52	16.1%
Aug	827	4.10	3.78	15.96	15.04	5.7%
Sep	822	2.79	4.39	15.86	16.79	−5.9%
Total	5186	10.67	8.74	26.29	23.73	9.7%
MLD Criteria = 0.3°C						
Apr	776	23.92	19.07	48.59	43.53	10.4%
May	925	13.80	9.85	34.92	31.30	10.4%
Jun	886	13.47	9.43	24.83	21.47	13.5%
Jul	950	9.94	6.59	17.48	14.26	18.4%
Aug	827	4.34	3.02	16.60	15.41	7.2%
Sep	822	2.55	3.64	16.19	16.64	−2.8%
Total	5186	11.26	8.49	28.59	25.61	10.4%
MLD Criteria = 0.5°C						
Apr	776	24.99	20.62	55.94	51.24	8.4%
May	925	14.23	10.75	40.50	37.29	7.9%
Jun	886	14.49	10.02	27.84	24.40	12.3%
Jul	950	10.90	6.68	18.61	15.12	18.8%
Aug	827	4.24	2.08	16.47	15.57	5.5%
Sep	822	1.53	2.42	16.85	17.29	−2.6%
Total	5186	11.67	8.65	32.33	29.51	8.7%

on September 18. When there is surface cooling, as usually occurs in the fall at these latitudes, and the thermocline of the GDEM profile is much weaker and deeper than the actual thermocline, the hindcast cannot but increase the initial, deep MLD bias.

Table 12 shows the monthly variation of the mean and rms MLD errors for GDEM and for the 72-h hindcasts for all the BTs taken between 20° and 50° N. The hindcast skill increases from April to July, decreases in August, and becomes negative in September. This seasonal trend in hindcast skill is generally consistent with previous hindcast results (Martin 1993; 1994a; 1994b).

IV. SUMMARY AND CONCLUSIONS

Previous investigations have shown that mixed-layer hindcasts with sufficiently accurate atmospheric forcing can improve the near-surface stratification and the MLD of climatological temperature profiles. Hindcast experiments were undertaken here to address two related questions: can mixed-layer hindcasts improve synthetic temperature profiles calculated from SSH and SST, and can skill in predicting MLD be demonstrated for mixed-layer hindcasts that use atmospheric forcing from the Navy's NOGAPS atmospheric model.

Data from OWS Victor were used to investigate the first question. Synthetic temperature and salinity profiles were calculated at Victor based on the SSH and SST of observed, deep, temperature profiles. Mixed-layer hindcasts were conducted that were initialized from the synthetic profiles, forced with wind stresses and heat fluxes calculated from 3-h meteorological observations at Victor, and integrated up to the time the observed profiles were taken. Different sets of hindcasts were conducted that were initialized from 12 to 120 h before the observed profile was taken. For each set of hindcasts, the MLDs of the synthetic and hindcast profiles were compared with the MLDs of the observed profiles, and mean and rms MLD errors were calculated on a monthly basis and an overall basis.

Overall, the rms MLD error of the hindcast profiles was lower than that of the synthetic profiles. However, the improvement was primarily due to the shallow MLD bias of the synthetic profiles relative to the observed MLDs in the fall and the winter. For the period May through August, when we would have expected the hindcasts to show the most skill, the rms MLD error of the hindcasts was generally worse than that of the synthetic profiles. Previous hindcast experiments at Victor had shown skill in hindcasting MLD in the spring and summer. However, the previous experiments used the more plentiful MBTs at Victor and were initialized from the observed MBTs rather than from climatological or synthetic profiles. An inspection of the individual hindcasts in June and July showed a number of instances where the observed MLD was deeper than would be expected during light winds and strong heating, and shallower than would be expected when the winds were stronger. Such discrepancies might be due to errors in the observed temperature profiles or to advection, since Victor is located in a strong frontal region.

The hindcast experiment was repeated using MBTs merged to the deep temperature profiles, with the MLD taken from the MBTs. It was considered that, since the MBT temperatures were recorded at 5-m intervals, they might provide more accurate MLDs. This experiment showed results that were not much better than those with the MLDs calculated from the deep temperature profiles. Again, most of the improvement of the hindcast MLD relative to the MLD of the synthetic profiles was due to the large shallow bias of the MLD of the synthetic profiles relative to that of the observed profiles.

An additional set of hindcast experiments was conducted with the Victor data to demonstrate that an SST change that occurs during the hindcasts can be corrected for, if necessary, by repeating the calculation of the synthetic profile with an adjustment of the observed SST to account for the change expected during the hindcast and then repeating the hindcast. In this way the SST of the hindcast temperature profile can be made to agree quite closely with the observed SST. By this method, the maximum monthly SST error of the hindcast temperature profiles at Victor was decreased from 1.02°C to 0.11°C, and the rms SST error calculated over all the hindcasts was reduced from 0.67°C to 0.06°C. This procedure can be used to correct the SST of synthetic profiles that are adjusted by a mixed-layer hindcast before they are input to a thermal analysis.

To investigate the skill of mixed-layer hindcasts forced by NOGAPS fields, NOGAPS surface wind stresses and heat fluxes and BT observations for April through September of 1990 were

acquired. Mixed-layer hindcasts were initialized from GDEM temperature and salinity profiles, integrated up to the time the observed BTs were taken with atmospheric forcing from NOGAPS, and verified against the observed BTs. Different sets of hindcasts were conducted with durations that ranged from 12 to 120 h.

Hindcast skill for MLD (the improvement of the rms hindcast error over the rms climatological error) was fairly low overall, about 4%. Hindcast skill was highest in the midlatitude North Atlantic (3% to 15%) and northeast Pacific (6% to 18%), and lowest in the northwest Pacific (−10% to 4%), and at low and high latitudes. The low hindcast skill obtained for the northwest Pacific relative to the northeast Pacific is consistent with some previous findings, and lends support to the hypothesis that hindcast skill for mixed-layer depth in the northwest Pacific is reduced by the frontal and advective activity in this region.

The MLDs from the GDEM climatological temperature profiles were consistently biased deep with respect to the observations. Of the areas investigated, the deepest biases (about 15 m) were in the North Atlantic and northeast Pacific. The hindcasts tended to show the most skill in those areas with the largest GDEM biases.

A point that these experiments brought out is that climatological errors will be minimized only when the climatological bias of the parameter or parameters that are important to the application for which the climatology is to be used are minimized. This point is logical and has certainly been made many times before, yet it can be easy to lose sight of, and it can sometimes be somewhat tricky to apply. For example, mean temperature profiles that are calculated by averaging temperatures at specific depths can be biased in terms of their MLD or the depth of the surface sound channel. So one has to ask the question as to what the mean profile is supposed to represent. This question is not always clear-cut, even when the application is known. For example, if the application is an acoustic range calculation, do we want a profile that gives the mean sound-channel depth, or the most likely sound-channel depth, or the mean acoustic range, or something else?

V. RECOMMENDATIONS

The mixed-layer hindcasts at Victor did not clearly demonstrate that such hindcasts can improve the near-surface stratification of synthetic temperature profiles relative to unbiased climatological estimates. Some possible reasons for the poor results are the effects of local advective processes, and the combination of noisy data and a small number of hindcast cases, which reduces the reliability of the error statistics. The best course to obtain more reliable results would be to conduct experiments with data that are known to be fairly accurate, so there would not be questions about the accuracy of the data affecting the conclusions.

The mixed-layer hindcasts performed with the NOGAPS atmospheric forcing do show some skill over climatology overall, and show a significant amount of skill in the midlatitude North Atlantic and northeast Pacific. However, there are questions as to why the results are worse in the northwest Pacific and at high and low latitudes. These experiments could be repeated with more recent data, e.g., data from 1991–1993, to see if the results are consistent with those obtained here for 1990. In addition, three-dimensional ocean circulation experiments with high horizontal and vertical resolution might shed some light on the degree to which advection impacts the MLD in such highly energetic areas as the northwest Pacific.

Climatological profiles can be biased with respect to such properties as mixed-layer depth and surface sound-channel depth. Consideration of this fact must be kept in mind when generating

and using climatological data for particular applications. Skill in predicting quantities, such as MLD, should be evaluated against unbiased climatological estimates to obtain a true measure of predictive skill (since comparisons against biased estimates tend to artificially inflate estimates of skill).

The accuracy of the BTs used in these experiments is crucial to obtaining reliable results. However, the BTs transmitted to FNMOC in real time are frequently sampled at fairly low vertical resolution, and some uncertainty exists as to the reliability of the temperature values and parameters, such as MLD calculated from such profiles. The automated systems currently being implemented to digitize BT records should help to improve the accuracy of the BTs that are being taken. This includes the inflection-point BTs that are transmitted to FNMOC in real time, as well as the full-resolution BTs (which are digitized at 1-m intervals) that eventually make their way to the archives at FNMOC, the National Ocean Data Center, and NAVOCEANO. Future studies of the type conducted here, which require accurate estimates of the near-surface thermal structure, should try to avoid inflection-point BT data in favor of high-resolution profiles.

VI. ACKNOWLEDGMENTS

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